On Wheeler's Quantum Circuit

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1 Introduction

The Meaning Circuit Hypothesis (MCH) is a synthesis of ideas providing John Wheeler's outline of ultimate physics, which he fine-tuned over several decades from the 1970s onward. It is a 'working hypothesis' in which 'existence is a 'meaning circuit"' that portrays the world as a "system self-synthesized by quantum networking." It was strongly advocated by him for roughly two decades and since then has had an increasingly strong impact on the approach of many investigators of quantum theory [1–3]; in particular, elements such as the quantum participator and 'it from bit' are now considered by others as candidate components of a foundation for quantum theory in which information is involved essentially; cf., e.g., [4–6]. Therefore, it is worthy of review and critique.[1]

[1]This paper is written on the occasion of the 60th birthday of Andrei Khrennikov, whose scientific life has included the service to the international physics community of organizing and running a continuous series of similarly interdisciplinary yearly conferences on the foundations of quantum theory that has spanned two decades, held in Växjö, Sweden, not far from Copenhagen, Denmark where Wheeler carried out his own postdoctoral studies with Niels Bohr. The Växjö quantum foundations conference series, which began with the new millennium, has been singular in its openness to a broad range of intellectual perspectives ranging from mathematical physics to the philosophy and history of science, all of which relate to this analysis and its fostering connections between quantum information studies and the foundations of quantum theory. It has been a privilege to participate in these meetings during which, as it turns out, my own work has run much of the gamut of areas touched on by the ideas of Wheeler's synthesis.

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Physical theory can be viewed as prescriptive and/or proscriptive, setting out what must happen and/or what is forbidden from happening in the physical world (cf., e.g. [9]), and the more metaphysically ambitious of physicists have used it to venture or support theses about what can, must, or cannot *exist* in the physical world, that is, its ontology which has often been rather imprecisely referred to in the physics literature as simply 'reality', as Wheeler himself did. Physical laws and a small number of mathematically oriented mechanical principles have been held to ground physics since at least the introduction of Newtonian mechanics; in its mature period, physics has considered equations of motion, conservation laws, or symmetries as illuminating the structure of physical world and its behavior. It has been possible for physicists to find, or come close to finding sets of axioms serving as a consistent mathematical basis for fundamental physics in addition to techniques for predicting physical behavior with high precision. However, for quantum theory, some of these accomplishments proved more illusive than in classical theory, leading to a re-evaluation of what had been considered self-evident and basic elements of physics.

The apparent foundational difficulties in quantum mechanics led Niels Bohr, Wheeler's postdoctoral supervisor to introduce new notions into the physics of the atomic and subatomic scale such as *the quantum phenomenon* and *the significance of measurement configuration to the definiteness of physical properties*, in addition to its defining element, the quantum of action, $\hbar$. Wheeler believed that "nobody has had a better picture of what quantum theory is and means" than Bohr [7], p. 59. Wheeler viewed the MCH as building "only a little [further] on the structure of Bohr's thinking" that showed "how information may underlie reality." He characterized his own approach to science as a sort of "radical conservative-ism," the conservative aspect being its building on the ideas of the founders of quantum mechanics including Bohr and its connection to experiment, and its radical aspect being the demotion of objective matter-energy and spacetime as fundamental and viewing them as arising from the processing and communication of information resulting from observation. The development of the MCH took place while quantum information science (cf., e.g. [8]), which relates physics, communication, and computation, was developing into a discernible subject area that has also recently been involved in the ongoing investigation of the foundations of quantum theory [3, 4]. Although it takes information as fundamental, the MCH goes far beyond standard quantum information science in its attempt to identify a common basis for both quantum theory and space-time theory—in Wheeler's view, by providing an answer to the question "Why the quantum?" that he saw as essential for understanding both these areas of physics and, indeed, for offering an ultimate conception of reality itself.

Up at least up until the early 1970s, for Wheeler and the physics community at large, the ontology of quantum theory was thought to be one of particles and/or fields (cf., e.g. [10]): The evolution of Wheeler's thinking preceding the MCH has been described as involving first "a major shift …concerning the fundamental ontology of the universe, from a world of particles (with fields as convenient fictions) to a world of fields (from which particle-like aspects can be derived). This shift can also be seen to have radically altered Wheeler's creative process" in conceiving new physical theory; cf. [11], Sect. 2. With the MCH, Wheeler attempted to shift from the conventional view, proposing that the quantum physical world picture is one where neither matter nor even space and time are primary but, instead, one where reality is 'built up' through the accumulation 'meaningful' information which, in his view, logically precedes them. This notion was captured by his now famous phrase "it from bit" and explicated in a process which he schematized as a circuit, the "meaning circuit" [3].[2] Following this lead, axiomatic foundations for physics involving information have recently been sought; for a review of these attempts, cf. [4].

Wheeler saw information-centric physics as the latest, "third era" of physics following "Era I—Motion with no explanation of motion: the parabola of Galileo and the ellipse of Kepler" and "Era II—Law with no explanation of law: Newton's laws of motion, Maxwell's thermodynamics, Einstein's geometrodynamics, modern chromodynamics, grand unified field theory, and string theory" ([1], p. 109). The closed nature of the universe, in particular, poses a problem: None of the conserved-quantity requirements can be applied there; "For example, every method to determine the mass-energy of a system goes back to or is in some way equivalent to placing a planet in orbit about that system, measuring the period and size of that orbit and applying Kepler's law,"

$$\text{mass (in cm)} = \left(\frac{2\pi}{\text{period, in cm of light travel time}}\right)^2 (\text{radius, in cm})^3 \quad (1)$$

([2], p. 14). Wheeler argued that physical laws as we have conceived them cannot be stated without the involvement of space and time, but space and time themselves cannot be fundamental, he claims, because they must come into existence at the putative beginning and possible end of the known universe according to observationally confirmed implications of general relativity such as an initial singularity and black holes.

Accordingly, it became Wheeler's view that future physical laws—of what he called "Era III" of the history of physics—cannot be absolute and invoke space and time as fundamental but must, instead, be mutable and, so, follow from deeper notion(s), including that of "the quantum" in terms of which space and time themselves can be understood. Through its explication of ultimate reality, Wheeler believed that the meaning circuit resolves two suggested paradoxes: one, that "The universe exists 'out there' independent of acts of registration, but the universe does not exist out there independent of acts of registration" captured by quantum theory; the other, that "The bounds of time tell us that physics comes to an end. Yet physics

[2] The "It from bit" slogan has been since been taken up by others, for example, Jeffrey Bub arguing "assuming the information-theoretic constraints are in fact satisfied in our world, no mechanical theory of quantum phenomena that includes an account of measurement interactions can be acceptable, and the appropriate aim of physics at the fundamental level then becomes the representation and manipulation of information" [12, 13], something extreme in that most physicists accord with the view of John Bell that measurement should be understood as just another physical process—most processes having nothing obvious to do with information—despite the quantum-*mechanical* measurement problem; cf. [14].

has always meant that which goes on its eternal way despite all surface changes in the appearance of things. Physics goes on, but physics stops; physics stops, but physics goes on" ([15], p. 341). Here, Wheeler's MCH hypothesis for resolving these paradoxes is reviewed and critiqued.

2 Development of the Meaning-Circuit Schema

Let us begin by briefly reviewing Wheeler's 'circuit' model for the conception of physical reality, its development, and a number of his arguments in support of it which are dealt with in greater detail in later sections. In this section, this is done primarily through the statements of Wheeler himself, in no small part because his discussions were often analogical and metaphorical, even poetic. The development of the MCH had begun at least as early as 1971 as evidenced by a presentation in Fribourg, "Beyond the End of Time," where the relationship of measurement and physics was considered. Wheeler began with the following question and answer. "[M]ay the universe in some strange sense be 'brought into being' by the participation of those who participate? …'Participator' is the incontrovertible new concept given by quantum mechanics: it strikes down the term 'observer' of classical theory, the man who stands behind the thick glass wall and watches what goes on without taking part. It can't be done" ([16], p. 180). This image encapsulates his view of the role of the 'observer' in physics, a notion invoked by Bohr's approach to quantum mechanics but with a reach extended beyond the physics of light and matter to that of space and time; his precise position as to what constitutes an 'observer' was to change over time and the *community* of observers, also mentioned by Bohr, would later be argued to play an even more central role in the meaning circuit model than the 'observer'.

In an article of 1973, "From Relativity to Mutability," Wheeler elaborated the metaphor of observer and glass barrier. "Even to observe so minuscule an object as an electron, he must shatter the glass. He must reach in. He must install his chosen measuring equipment. It is up to him to decide whether he shall measure position or momentum. To install the equipment to measure the one prevents and excludes his installing the equipment to measure the other. Moreover, the measurement changes the state of the electron. The universe will never afterwards be the same. To describe what has happened, one has to cross out that old word 'observer' and put in its place the new word 'participator'. In some strange sense the universe is a participatory universe" ([17], p. 244). The main differences in this approach from that of classical physics are that the physical state and even "the universe" is supposed to change as a result of observations and their communication, not merely that any measurement involves physical interaction and a record of the result. Wheeler would later offer a corresponding experiment as a concrete illustration of such cosmic participation.

In a presentation following within a year's time, "Is Physics Legislated by Cosmogony," Wheeler turned more precisely to the spatial aspect of the universe, "No one see any longer how to defend the view that geometry was created on 'Day One' of creation, and quantized on Day Two.' More reasonable today would appear the contrary view, that 'the advent of the quantum principle marked Day One, and out of the quantum principle geometry and particles were both somehow built on Day Two"' ([18], p. 544). So, it appears to him that "[the quantum principle] promotes observer to participator", one whose participatory observations are enabled on Day Two ([18], p. 560). For Wheeler, the 'quantum principle' also "tells what question it makes sense for the observer to ask" in order to obtain 'meaningful' observations, which are of greater significance to understanding reality than theory is ([18], p. 544). In "Include the Observer in the Wave Function?", a paper prepared for a May, 1974 conference in Strasbourg, Wheeler wrote in section entitled "The Role of the Observer" that "That the 'observer' should have a special place in the scheme of quantum mechanics has often been contested. Bohr himself argued at one point that an 'irreversible amplification process' is all it takes to 'complete' a measurement, only to stress on other occasions that an observation is only complete when there is an observer …Fission, and by extension the pulse of a Geiger counter and the blackening of a silver halide crystal, are only then guaranteed to be indelible in the relevant sense when the act has registered in the consciousness of the observer"—this conclusion supported by the in principle reversibility of fission with the addition of "'mirrors' set up to give sufficient time delays and sufficient accuracy of return of the outgoing particles and radiation…" to reverse it [19]. Here, Wheeler suggests that it is the character of observation by a conscious observer that is necessary for and precipitates the novel change of physical state involved in quantum theory and so alters existence at a basic level with each "meaningful" measurement.

In a following, 1975 presentation, "Genesis and Observership," Wheeler went on exactly to explore "the working hypothesis that 'observership is the mechanism of genesis"' as an answer to Leibniz' question "'Why is there something rather than nothing"' which "William James translated" into "the more meaningful …'How comes the world to be here'…" ([2], p. 3), and the position that "Quantum mechanics promotes the mere 'observer of reality' to 'participator in the defining of reality'. It demolishes the view that the universe sits 'out there'." Thus, Wheeler rejects any fully objective view of reality ([2], pp. 5–6), which for him came to be one *constructed* by physics of a kind that is intimately connected with a process of observation yielding information which is considered primary to it.[3] Four ideas, "(1) 'mutability', (2) 'no ultimate underpinning', (3) 'observership as prerequisite for genesis' …(4) 'observer-participator as definer of reality'," were presented as bearing on the origin of existence. Wheeler argued that to lend coherence to this collection and provide an answer "…demands a central theme and thesis. …Up to now, however, no pattern suggests itself from the available clues except this, to interpret quantum mechanics as evidence for the tie between genesis and observership" ([2], p. 8). He also recalled

[3] This is in direct opposition to the position held by many physicists, for example, John von Neumann, that physical theories are required to accommodate a physical correlate to subjective perception according to the principle of psycho-physical parallelism: "it is a fundamental requirement of the scientific viewpoint—the so-called principle of psycho-physical parallelism—that it must be possible to describe the extraphysical process of the subjective perception as if it were in reality in the physical world—i.e., to assign to it parts equivalent physical processes in the objective environment, in ordinary space" ([20], pp. 418–419).

"Bohr's words about the Schrödinger state function, 'that we are here dealing with a purely symbolic procedure, the unambiguous physical interpretation of which, in the last resort, requires a reference to a complete experimental arrangement."' Wheeler adds "'that all departures from common language and ordinary logic are entirely avoided by reserving the word 'phenomenon' solely for reference to unambiguously communicable information'" ([2], p. 24). This already indicates the significance of information theory in Wheeler's ultimate scheme which connects it with Copenhagen approach to interpreting the quantum formalism wherein meaningful information is the sort of information *communicable within a community* of participators.

In a 1977 magnum opus, the lecture "Frontiers of Time" for Course LXXII of the Enrico Fermi School of Physics in Varenna, Wheeler reiterated Bohr's reply to Einstein that the "…conditions [of measurement] constitute an inherent element of any phenomenon to which the term 'physical reality' can be attached.' …[This requires] a final renunciation of the classical ideal of causality and a radical revision of our attitude towards the problem of physical reality"' ([21], p. 7). Under the MCH, all physical form is to arise through acts of observer-participation, even that of space-time: "…individual events. Events beyond law. Events so numerous and so uncoordinated that, flaunting their freedom from formula, they yet fabricate all physical form …Nowhere more clearly than in the ending of spacetime are we warned that time is not an ultimate category in the description of nature" ([21], p. 143). To support the claim, Wheeler offered an argument involving a defining characteristic of the physics of his Era III: "Law without law." "The absolute central point would seem to be this: The universe had to have a way to come into being out of nothingness, with no prior laws, no Swiss watchworks, no nucleus of crystallization to help it—as on a more modest level, we believe, life came into being out of lifeless matter with no prior life to guide the process. …" where "when we speak of nothingness we mean nothingness: neither structure, nor law, nor plan" ([21], p. 16). In the anticipated Era III of physics, he held, it will be held that only chance events take place with collective behavior agrees with the laws of Era II in the "everyday world." The connection to the novelty of quantum theory is made specifically as follows. "The necessity for [the] line of separation [between the observer-participant and the system under view] is the most mysterious feature of the quantum. We take that demarcation as being, if not the central principle, the clue to the central principle in constructing out of nothing everything" ([21], p. 17).

Although Wheeler suggested that Bohr rejected a universe that is simply "out there," he nonetheless pointed out that "For Bohr the central point is not 'consciousness,' not even an 'observer,' but an experimental device—grain of silver bromide, Geiger counter, retina of the eye–capable of an "irreversible act of amplification". This act brings the measuring process to a 'close.' Only then, he emphasized, is a person able "to describe the result of the measurement to another in plain language" ([21], p. 19). For Wheeler, this constraint is understood to extend to the earliest moment of the universe, so that "The universe is a self-excited circuit. As it expands, cools and develops, it gives rise to observer-participancy. Observer-participancy in turn gives what we call 'tangible reality' to the universe" ([21], pp. 22–25). As an example of the manifestation of observer-participancy and its cosmogonic significance, Wheeler considered the measurement of photon properties at large times. "There is no more remarkable feature of this quantum world than the strange coupling it brings about between future and past, between (1) the way one will choose to orient his polarization analyzers two years down the road and (2) what one can then say about the photons that already—as judged by us now—had their genesis 3 years ago. There is a sense in which the polarization of those photons, already on their way, 'was' brought into being by the disposition of the polarization analyzers that the observer has yet to make and will make. Moreover there is no difference in principle whether the time between the emission of a photon and its detection is 5 years; or a nanosecond, as it is when one is looking at an object a foot away; or 10^{10} years, as it is when one is receiving direct or indirect radiative evidence of what went on in the first few seconds after the big bang. In each case what one chooses to ask …forms an inseparable part of a phenomenon that in earlier thinking one would have said had'already happened'. In this sense it is incontrovertible that the observer is participator in genesis" ([2], pp. 24–25).

This 'coupling' raises the question of the definiteness and ontological status of the past in general. "How can an observation made now have any influence whatsoever on what has already happened?" along with the point that in the quantum realm, "'what has already happened' is not so easy to say" ([21], pp. 25–26), pointing to the notion of a delayed-choice experiment, one spanning nearly the duration of the history of the universe. "The photons of the primordial cosmic fireball radiation that enter our telescope today, we customarily assume, already had an existence in the very earliest days of the universe long before life evolved. However, not until we catch a particular one of those photons in a particular state with particular parameters, not until the elementary phenomenon is an observed phenomenon, do we have the right even to call it a phenomenon" and, as for the "unbelievably more numerous relict photons that escape our telescope…their 'reality' is of a much paler and more theoretic hue"; ibid., pp. 26–28. And, while there is some tension in the very way these sentences are formulated, in that Wheeler is talking about "catching photons" that become "phenomena," if one keeps in mind that free photons can be thought of—indeed, at the moment, are standardly thought of—as excitations of quantum fields rather than as individual systems of their own, it is a consistently posed statement that relates to more than the polarization but even the presence of each photon. Accordingly, "an immense labor of imagination and theory" is required to provide a conception of physical reality grounded in intersubjectively communicated observation results; ibid., p. 28.

Turning to space and time themselves, Wheeler argued that spacetime is a "deterministic classical concept, applicable only at the level of approximation theory" in light of complementarity ([21], pp. 36–37) and asks "how can any elementary building process be an elementary process for building existence and law unless it transcends the category of time? To identify an elementary building process that transcends time…The act of observer-participancy in such an experiment, right now, irretrievably alters what we have the right to say about 'the past.' In that sense, that carefully restricted sense, that act is an inescapable part of the actual building of 'the past.'"; [21], pp. 42–43. He held that, given both quantum theory and geometrodynamics, “time is transcended, laws are mutable, and observer-participancy matters. ‘Before’ and ‘after’ don’t rule everywhere, as witness quantum fluctuations in the geometry of space at the scale of the Planck distance. Therefore ‘before’ and ‘after’ cannot legalistically rule anywhere. Even at the classical level, Einstein’s standard closed-space cosmology denies all meaning to ‘before the big bang’ and ‘after the big crunch.’ Time cannot be an ultimate category in the description of nature. We cannot expect to understand genesis until we rise to an outlook that transcends time …There never was a law of physics that did not require space and time for its statement. With collapse the framework falls down for everything one ever called a law. The laws of physics were not installed in advance by a Swiss watchmaker, nor can they endure from everlasting to everlasting. They must have come into being” ([21], pp. 44–45), the Planck length being

$$l_P = (\hbar G/c^3)^{1/2} , \tag{2}$$

where G is the gravitational constant, c is the speed of light in vacuum, and $\hbar$ is the reduced Planck constant (the quantum of action), and all constants on the right-hand side are all given the value 1. And so, he argued, determinism must be abandoned: “one has to forgo that view of nature in which every event, past, present, or future, occupies its preordained position in a grand catalog called ‘spacetime.’ There is no spacetime, there is no time, there is no before, there is no after. The question what happens ‘next’ is without meaning” ([21], p. 105).

However, Wheeler also recognized that there are apparent limitations to a physics based on participancy; he instructs one, at least for now, as follows. “Don’t try to ‘take time apart’ into elementary quantum acts of observer-participatorship out of which we conceive it—and everything—to be built. Instead, sticking to the solid ground of physics as we know it, identify domains where familiar concepts of time and causality come to the limit of applicability and have to be modified. We have just finished exploring one such frontier. We have seen how both time and spacetime, according to existing theory, lose all application at the Planck distance and the Planck time; but how out of a description that transcends time–out of superspace–we come back in the appropriate correspondence principle limit to familiar views of time” ([21], p. 117), where the Planck time is

$$t_P = (\hbar G/c^5)^{1/2} . \tag{3}$$

Accepting this view of space and time, one must of course contend with the implications for causality, which Wheeler did by considering, as a basic example, the situation of the emission of electromagnetic radiation in a system of point charges coupled with each other by elementary electromagnetic actions-across-a-distance—which are individually time symmetric in the sense that the force exerted on a particle by one particle on the other is given by half the retarded field of the first, as usually calculated, plus half the advanced field—and the particle is suddenly accelerated.

> This links past and future in a maze of backward and forward running light rays. Nowhere can the slightest change be made without altering motions everywhere into the indefinite past and future. we want to establish in this one example a point of more general application:

> The apparent inability of an action taken now to influence the past by no means rules out a direct influence of the present in 'bringing about that which we call the past.' It is in no way suggested here that this is the actual mechanics by which acts of observer-participancy in the present bring [about] that which we call the tangible or communicable reality of the universe at an era when no observers existed. That is a deeper question with which physics is not yet prepared to deal. However, one is open to believe that the kind of considerations that elucidate the one may clarify the other ([21], p. 118).[4]

Similarly, "the irreversibility of the emission process is a phenomenon of statistical mechanics connected with the asymmetry of the initial conditions with respect to time…an order in time, ostensibly causal, can originate from an underlying machinery that is very far from causal. …we here have a sample law, causality, emerging from a description of nature that contains no such law" ([21], pp. 120–121).

Wheeler continued his investigation of physical law as mutable and the possibility of the non-primacy of space-time in a 1979 article "Beyond the Black Hole."

> 'Physical space-time is not mathematical space-time' is the one lesson of mutability; the other, 'Physical law is not ideal mathematical law.' Law that comes into being at the beginning of time and fades away at the end of time cannot be forever 100% accurate. Moreover, it must have come into being without anything to guide it into being…The laws of physics themselves, coming into being and fading out of existence: in what else can they have their root but billions upon billions of acts of chance? What way is there to build law without law, field without field, substance without substance except 'Individual events. Events beyond law. Events so numerous and so uncoordinated that, flaunting their freedom from formula, they yet fabricate firm form?' ([15], p. 352).

Several of the above ideas were reiterated along with some other contributions that quickly followed in 1980 and 1981 to form a shorter 1983 article "Law without Law" ([23], pp. 182–213). Wheeler had raised a challenge to physics with these speculative arguments, and he was optimistic regarding their significance and ability to explain how 'something may arise from nothing.' "No test of these views looks more like being someday doable, nor more interesting and more instructive, than a derivation of the structure of quantum theory from the requirement that everything have a way to come into being out of nothing. If you would have an epitome of this summary, let it be this: Nothing. No time. The line. Acts. Statistics. Law. Spacetime. Substance. Observer-participant Closed circuit. Test." ([21], p. 46).

Wheeler offered a comprehensive model illustrating the structure of the MCH in a presentation of 1986 entitled "How come the quantum?". In this model, discussed in detail below in Sects. 3 and 5, the establishment of physical reality is explained as follows.

> Physics gives rise, …to light, pressure, and sound. They provide means of communication, of the importance of which Niels Bohr notes, '. . . every analysis of the conditions of

[4] As he was later to describe this, in the mid-1980s, one finds "an unbelievable maze of light-like connections running backward and forward in time. Nevertheless, when the number of particles is sufficiently great to guarantee absorption of all radiation, the maze translates itself into the familiar full-strength pure retarded electromagnetic interactions, plus the familiar radiative reaction. No contradiction with everyday notions of causality is to be seen. No less has to be expected of an information-theoretic account of physics;" [22], p. 31.

> human knowledge must rest on considerations of the character and scope of our means of communication. Physics is also the foundation of chemistry and biology, out of which arise communicators.…' From meaning back to physics, the circuit under examination makes its way by a less apparent or underground sequence of linkages. Meaning rests on action. Action forces the choosing between complementary questions and the distinguishing of answers. Distinguishability, in the realm of complementary possibilities, demands for its measurement complex probability amplitudes. The change in the phase of a complex probability amplitude around a closed circuit not only measures the flux of field through that circuit, but can even be regarded as the definition and very essence of that field. Fields, in turn, can be viewed as the building stuff of particles; and fields plus particles generate the world of physics with which the hypothesized meaning circuit began ([3], pp. 304–305).

Here, Wheeler's 'meaning' is "the joint product of all the evidence that is available to those who communicate." (This is the subject of Sect. 5.4 below.) After having presented the elements of the MCH by the mid-1980s, Wheeler continued to clarify his views on its detail and implications. For example, in a 1988 follow-up "World as System Self-Synthesized by Quantum Networking," he presents the MCH "in contrast to the view that the universe is a machine governed by some magic equation," it is the "view that the world is a self-synthesizing system of existences, built on observer-participancy via a network of elementary quantum phenomena" [1].

Wheeler's goal was a conception of the physical world in which space and time are no longer considered primary, incorporating the novelties of quantum mechanics in a way consistent with the known natural science, which had been developed with a methodology similar to that used in discovering classical physics but eschewing the mechanistic approach in favor of a focus on communicable information. He believed that the "elementary quantum phenomenon is the strangest thing in this strange world. It is strange because it has no localization in space or time. It is strange because it has a pure yes-no character—one bit of meaning. It is strange because it is more deeply dyed with an information-theoretic color than anything in all physics" ([1], p. 115). Broadly speaking, with the MCH Wheeler went beyond Bohr's position that science, as a human activity, involves the communication of results of its contributors, to a direct grounding of physical systems and processes in the information that is communicated within science. Nonetheless, his extension to the experimental 'asking questions of nature' remains in the spirit of Bohr's understanding of physics, in particular, in its use of the notion of the complementary nature of physical measurements [24]. "In brief, complementarity symbolizes the necessity to choose a question before we can expect an answer…We once thought, with Einstein, that nature exists 'out there', independent of us. Then we discovered—thanks to Bohr and Heisenberg—that it does not" ([1], p. 113).[5]

Throughout the development of his MCH, Wheeler was either vague or vacillated with regard to the question of whether there is a necessary role for consciousness—something he consistently recognized as itself not well understood by science—in elementary quantum phenomena. Finally, in the 1990s, he expressed an affinity for

[5] One should take care not to accept this statement of Wheeler as a correct understanding of the views of Bohr and Heisenberg themselves, which often differ from those of their interpreters like Wheeler; cf., e.g. [25].

the notion of quantum potentiality, which plays a central role in the Heisenberg's mature understanding of the quantum state as indicating a genuine mode of existence and not mere logical possibility; Heisenberg's later view was that measurement outcomes and observations arise independently of human participation, even if they are brought about only through coincidence with the greater physical world; cf. [26]. In the following section, the central elements of Wheeler's conception of physics as represented via the MCH are considered in succession. These include "question and answer feature of the elementary quantum phenomenon" and the concomitant role of distinguishability in it, why the quantum probability amplitude is complex, the attribution of meaning to measurement results, and the circuit as the alternative to a hierarchical built upon a traditional foundation, taking into consideration the issues with his MC model, the role of 'communication' in physics, and the 'It from bit' thesis. Wheeler himself noted some difficulties with the assertion of aspects of this synthesis, and these considered along with a number of other deep concerns.

3 How Come the Quantum? A Critique

Although information plays a fundamental role according to the MCH, the physical mechanism involved in measurement is nearly as significant: "…the meaning-creating community of observer-participants, past, present, and future, is brought into being by the machinery of the world." Indeed, consistently with his late affinity with the potentiality interpretation of quantum state amplitudes in the 1990s, the "machinery" and that the information obtained using it in measurement can be understood on par with each other, for it is the machinery of the world that provides the signal-records through which information is obtained. This machinery and the information it provides to observers relate to *different*, however intimately related domains—those of existence and human knowledge of that existence—that Wheeler failed to adequately distinguish in his writings of the 1970 and 1980s. The hypothesis "goes on to interpret this very world of past, present, and future, and of space, time, and fields, to be (despite all its apparent continuity, immensity, and independence from us) a construction of imagination and theory" where elementary quantum phenomena form "the iron posts of discrete acts of observer-participancy, the ant-like but magnificent labor of a community stretching from far in the past to even farther in the future" and time is "not primordial, precise, and supplied from outside physics, but secondary, approximate, and derived" [3], p. 313. The observed and communicated bits of information are considered the strongest elements of a reality understood as constructed from these facts and scientific knowledge. Yet, consciousness is not required for the signaling of these bits, only for the existence of knowledge to which they may give rise. And, in the long run, Wheeler relinquished the view that observation and measurement *require* consciousness.

And, despite his strong views as to the significance of measurement and information theory to physics, Wheeler was certainly *not* advocating a form of idealism; rather, like Bohr, he put forward a very subtle form of realism, a 'participatory realism.' Wheeler rhetorically raised the question, "How does quantum mechanics today differ from what Bishop George Berkeley told us two centuries ago, '*Esse est percipi*,' to be is to be perceived? …Yes, and in an important way. Berkeley—like all of us under everyday circumstances—deals with multiple quantum processes …Anything macroscopic that happened in the past makes, we know, a rich fallout of consequences in the present. …the number of quanta that come into play is so enormous that the unseen quantum individuality of the act of observation can hardly be said to influence the event observed"; [27], p. 186. And just this is required for the occurrence of an observed quantum phenomenon capable of yielding the communicable information so important to his meaning-circuit model, its "genesis." Two crucial questions are involved in the process of 'genesis' Wheeler hypothesizes: (i) what the 'density' (variable) of such signposts in reality is at various stages of its history, and (ii) how essential, if at all, to their appearance living or conscious observers (who when the universe existed) are.

Regarding (i), Wheeler commented that "If life wins all, then the number of bits of information being exchanged per second can be expected to rise enormously compared to that number rate today. …And how great must that future total be—tally as it is of times past—to furnish enough iron posts of observation to bear the smooth plaster which we of today call existence? Bits needed. Bits available. Calculate each. Compare. This double undertaking, if and when it becomes feasible, will mark the passage from clues about existence to testable theory of existence" [1], p. 126. However, this is an essentially epistemic question having to do with the facts serving as the basis of our own theorizing rather than with the existence of the physical world that the resulting physical theories are to describe and explain. While it is true that the degrees of (in)determinacy of properties of subatomic systems relate to measurement, the Heisenberg indeterminacy principle—which is what is most relevant here in the quantum realm—regards the relative definiteness involved in the complementary measurement activities that themselves still require physically distinct and mutually excluding apparatus configurations to yield information to observers.

Regarding (ii), Wheeler proposed that, due to presence of the quantum of action, "The observer is elevated from 'observer' to 'participator.' What philosophy suggested in times past, the central feature of quantum mechanics tells us today with impressive force: In some strange sense this is a participatory universe"; [2], pp. 5–6. Space, time, particles, and fields are all "brought into being" from quantum information-yielding events, and only by a "dethronement from primordial and precise to secondary, approximate and derived can 'time' be reduced, like all the rest of physics, to an information-theoretic foundation" [22], p. 30. Thus, the second question is again one about the process of obtaining information by observers and the manner in which that information is rendered meaningful and communicated, which is an epistemic one. Wheeler argued that for this "we possess no other model [than the Meaning Circuit] that puts in central place the quantum and the question of 'how come the quantum?"' [3]. However, this is not so. One need not assume that the entities of physics are *brought into being* in information-transfer events simply because of the presence of the quantum of action in measurement interactions. Standard quantum measurement theory explains how measurements provide records of the properties of quantum systems in the past whose possible different properties upon measurement are made definite at some moment—much, though of course somewhat differently, as the exact color of Caesar's clothing on a particular day could have been more or less better inferred, even from an extreme temporal distance, by an author whose writings we now possess, and be useful as a fact knowable to historians to be combined with other possibly later-obtained information—providing data to those who might attribute it meaning and communicate it between themselves. Wheeler's MCH is a hypothesis that transcends physics and concerns itself with the manner in which physical knowledge and theory arise, claiming that these are the determinants of existence but without sufficient justification.[6]

To reassure those who might be concerned about that the role given observer in the MCH might threaten the unity of the universe, Wheeler notes that his view of quantum theory does not amount to a "many worlds" view: "What keeps the images of something 'out there' from degenerating into separate and private universes: one observer, one universe, another observer, another universe? That is prevented by the very solidity of those iron posts, the elementary acts of observer-participancy. That is the importance of Bohr's point that no observation is an observation unless we can communicated the results of that observation to others in plain language"; [27], p. 203. Wheeler argued further that the *self* is not independent of others.

> The heart of the matter is the word self. What is to be understood by the word self we are perhaps beginning to understand today as well as some of the ancients did. We know that in the last analysis there is no such thing as self. There is not a word we speak, a concept, we use, a thought we think which does not arise, directly or indirectly, from our membership in the larger community. On that community the mind is as dependent as is the computer. A computer with no programming is no computer. …programming by parents and community that makes a mind a mind. The heart of mind is programming, and the heart of programming is communication. ([1], p. 127)

Thus, "*Communication* is the essential idea. If I see something, but I'm not sure whether it's a dream or reality, there's hardly a better test than to check whether someone else is aware of it and can confirm my observations" [7], p. 62. This is certainly important for establishing the objectivity of data of the senses but, again, is beside the point for physics itself; it regards the validity of data, not its ultimate origins.

Thus, the MC model portrays physical systems and their behavior between measurements as ultimately (inter)subjective creations of the scientific community based on the physical facts (phenomena) arising through measurement. This model is illustrated by Wheeler as a corn-kernel shaped 'meaning circuit,' sketched metaphorically as running about a slope, with the abstract elements—questions and quantum formalism—underground and the signaling apparatus sub-grouped into "means of communication" and "communicators" above ground: its two large parts are shown as two towers labeled "physics," at base and "meaning," at peak. That "part of circuit…is well known"; [28], p. 404. However, no detail is offered in this model regarding the

[6] Indeed, Wheeler repeatedly admits that it is precisely the nature of cognition located in the meaning circuit which is inadequately understood, as shown below.

important distinction between meaning and information/data; as with consciousness, Wheeler regarded this as a part of science that is only emerging: "New aspects of what we mean by 'meaning' are beginning to emerge from recent studies in computer science and in information theory that put quantum at center stage"; [28], p. 404. What is said regarding meaning is that physics "gives rise to chemistry and biology and, through them, to communica*tors*. The communicators and the communications between them generate meaning. This is the first part of the meaning circuit. It makes meaning the child of physics. Physics itself, however, according to this view, is also the child of meaning. The return portion of the meaning circuit, the connection that leads back from meaning to physics, runs 'underground,' out of sight." [22], p. 25. For Wheeler, the elementary quantum phenomenon, which is connected with the summit of his circuit and is a notion the origins of which are clearly traceable to Bohr, "displays two characteristic features: (1) complementarity in the choice of the question and (2) statistics in the distinguishing of the answer." [3], p. 306. The important pair of successive points *below ground* labeled "ask question" and "distinguish the answer" are the two elements of the extraction of information, the basis-choice/measurement as the decoding of information carried by the state-signal—do clearly appear in it, although the opposite side of the loop from this pair; the referent, and hence 'meaning', of a click depends on the physical measurement basis.

Although communication theory standardly connects information and physics via the notion of signaling and provides methods for the quantification of information that can be encoded in signals, the relation between physics and information suggested by Wheeler is anything but standard: It is strongly reductionist in the opposite sense from what is the standard relation where systems in physical states are understood to provide signals that *could be used to communicate information* via a freely chosen encoding/decoding method; instead, he views physical systems as *made of and constructed from information*. Wheeler referred to elementary quantum phenomena as being of a "meaning-theoretical character" [7], p. 66, indicating a conflation of two matters: (i) recording and collecting data and (ii) giving meaning to data.[7] Data collection, on the one hand, and the interpretation of data arising in physical events in terms of the elements of theory (much less the creation of theories of the world or reality), on the other, are very different. Indeed, the operation of the circuit—its provision of meaningful experimental results—was summarized by Wheeler as follows. "Evidence available to the communicator comes from the asking of a question [via an experiment] and the distinguishing of an answer" by observing the result of it ([3], p. 305).

Wheeler offered very different examples of the putative reduction of an 'it' to a 'bit' via 'it from bit', a relatively exotic example being that of a black hole: He claimed that "The it, the area of the horizon of a black hole, expressed in units of the basic Bekenstein-Hawking area

$$4(\hbar G/c^3)\log_e 2\,, \tag{4}$$

[7] And this would be so even if he were understood to considering primarily cognitive.

is given by the bit count, N, of that black hole. Here N represents the number of bits of information it could have taken to distinguish the initial configuration of particles and fields that fell in to make this particular black hole from the 2^N alternative quantum configurations that would have produced a black hole externally identical to it" ([29], p. 555).[8] A less exotic example he considered repeatedly in his writing is that of the amount of information obtained in the determining the polarization of a photon, one bit.[9] One could ask, considering an even more concrete example, the *spin* of an electron, does one bit actually constitute the *spin* and does this bit, together with the other bits corresponding to distinguishing the other properties of the electron, *constitute* the electron? The important point to note here is that, on this view, a physical system is no longer considered physical in any usual sense but rather is *only the information corresponding to its state*.

Perhaps the most striking of the examples of 'it from bit' Wheeler provides is that of "reducing the 'how much' of the field measurement to the 'many a chance yes-no' of elemental quantum phenomena" [22], p. 29. This is to be accomplished through dichotomous measurement results signaled by detector clicks: to find the magnetic field strength in a region, "it is enough to illuminate the atom [chosen to observe a Zeeman shift] with monochromatic radiation of a precisely chosen frequency…just enough for photoionization when the magnetic field is 'on'. The electron, once freed, is drawn…into a device like a photomultiplier. A pulse is registered on a counter. The elemental quantum phenomenon is brought to a close by this irreversible act of amplification. An item of information is generated which one person can communicate to another 'in plain language'. Out of sufficiently many such items of 'yes, no' information obtained for slightly different values of frequency…we determine more and more precisely the value of the Zeeman level shift and measure—and define—the magnetic field" ([22], p. 29). Perhaps, but this does not mean that the magnetic field has thereby come into existence; rather, its properties merely become *more or less definite and knowable* to those contemplating the corresponding experimental records, even when that record is a flash recorded by the nervous system of a human being and immediately attended to by its conscious mind.[10]

Despite the circuitous character of his view of experimentation, Wheeler took an ontological-reductionist as well as theory-reductionist stance wherein all of reality is 'theory' constructed from and relating such insubstantial information-theoretically quantifiable and elementary quantum phenomena to each other, conditioned on the circumstances of their recording. He reduces matter and space-time to 'meaning' in his conception of physical reality. "Physical space-time is not mathematical space-time" and "Physical law is not ideal mathematical law" ([15], p. 352). The issues noted in this section are delved into in greater detail in Sect. 5, below, after the consideration in the next section of Wheeler's views on quantum phenomena and the world

[8] The event horizon of the black hole is implicitly considered here identical with the area.

[9] Again, however, this is as a matter of fact dependent on the circumstances of preparation and encoding/decoding assumed and would be rather *at most* one bit.

[10] It is noteworthy that Wheeler's views in the 1990s which brought quantum potentiality into consideration, appear to recognize this.